Predicting the Distribution and Properties of Buried Submarine Topography on Continental Shelves

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LONG-TERM GOALS

The long-term goal of the Geoclutter modeling project is to predict the distribution and properties of buried channels that may be responsible for geoclutter on continental margins of interest.

OBJECTIVES

The overall objectives of our project are 1) to determine the characteristics of channel features that can form when the present continental shelf is subaerially exposed during low sea-level conditions and 2) to determine whether these features would be buried when sea-level returned to its present position and, if so, how deeply. During FY01, our objectives have been to adapt the model to run on real topography with model parameters representative of mid-latitude coastal plain environments, to perform sensitivity tests of model and landscape parameters, to apply the model to shelf topography found on the modern New Jersey and Virginia continental shelves, to begin to test the model using relevant terrestrial and marine data, and to develop an approach for adding shelf processes to the landscape evolution model.

APPROACH

Our approach is to develop numerical simulation models of landscape evolution and shelf sediment transport to investigate the development of topography on the shelf during sea-level low stands and the burial of that topography during high sea-level conditions. Our model is based on Alan Howard's landscape evolution model. Alan Howard and Sergio Fagherazzi (post-doc) are adapting and testing the model of channel formation for coastal plain settings. Patricia Wiberg and Sergio Fagherazzi are developing and implementing a diffusive characterization of shelf processes in the model.

WORK COMPLETED

We have an operational version of the landscape evolution model, parameterized for coastal plain environments. This has been run to simulate channel formation on existing shelf topography from

New Jersey and Virginia. We have developed a diffusive representation of shelf processes that is being incorporated into the model.

RESULTS

Channel formation on an exposed continental shelf using modern initial shelf topography

Fluvial erosion during Quaternary sea level lowstands exposed continental shelves to a depth of more than –120 meters. During these lowstands the exposed shelves were subject to fluvial and mass wasting erosional processes that created dendritic channel networks, some of which are partially preserved beneath shallow marine and coastal deposits. During the past year, the drainage basin model of (Howard 1994; Howard 1997) has been adapted for simulation of erosion on the continental shelves and preliminary simulations have been conducted.

Model Parameterization: The most important processes requiring explicit physical scaling and calibration are mass-wasting, sediment transport and deposition in alluvial channels, and erosion of bedrock-floored channels. Mass-wasting is the downslope movement of the surface soil and regolith and may include diffusive creep, accelerated mass wasting for slopes approaching a critical angle of stability, and landsliding. Reported values of creep diffusivity range from 0.0001 to 0.06 $m^3/(m\text{-}yr)$. Values towards the lower end of this range are typical of humid temperate landscapes such as the modern Appalachian region. Threshold slopes generally range from about 35 to 50 degrees. We assume landsliding is unimportant unless such features become apparent in exploration of buried low stand topography. Fluvial sediment transport on channel beds is initially assumed to be composed primarily of sandy sediments, and the Einstein-Brown sediment transport relationship has been assumed. Channel geometry and hydrology is parameterized by summary equations of hydraulic geometry (Howard 1994), and initial values of hydraulic geometry parameters were adopted from measurements reported in Brush (1961). The initial simulations assume that erosion rates of detachment-limited channels are proportional to the shear stress exerted on the bed by bankfull discharges, with erosion commencing only when a critical shear stress is exceeded. Bed sediment erodibility is estimated from ten years of measurements of channel erosion in poorly consolidated coastal plain sediments exposed in a Virginia borrow pit (Howard and Kerby 1983). Critical values of shear stress that must be exceeded to erode channels depends strongly on the nature of the substrate and the degree of vegetation cover. Values for bare sediments are about 0.1 to 1.0 N/m^2, whereas for vegetated soil values can range up to 3000 N/m^2.

Preliminary Simulation: We have used modern offshore topography of the Atlantic coastal plain as initial conditions for our preliminary simulations of continental shelf erosion during sea-level lowstands. For simplicity, our preliminary simulations assume instantaneous exposure of the continental shelf to a depth of –120m and its exposure for a period of 500 years to terrestrial erosion. An example simulation is shown in Figures 1a and 1b. Figure 1a is a portion of the modern continental shelf offshore of the eastern shore of Virginia. A small portion of the Delmarva Peninsula lies in the upper right corner. The heads of the Norfolk and Washington canyons are at the lower left (bathymetry is cut off at –120 m). The region portrayed is 128km x 128km with 500m grid cell resolution. North is approximately to the right. Offshore ridges dominate shelf topography.

Figure 1b shows the results of 500 years of simulated erosion of the continental shelf. In this simulation we assume that diffusive slope processes are unimportant at this scale and that the critical

shear stress is negligible. Several general observations characterize the simulations (including other simulations not presented here):
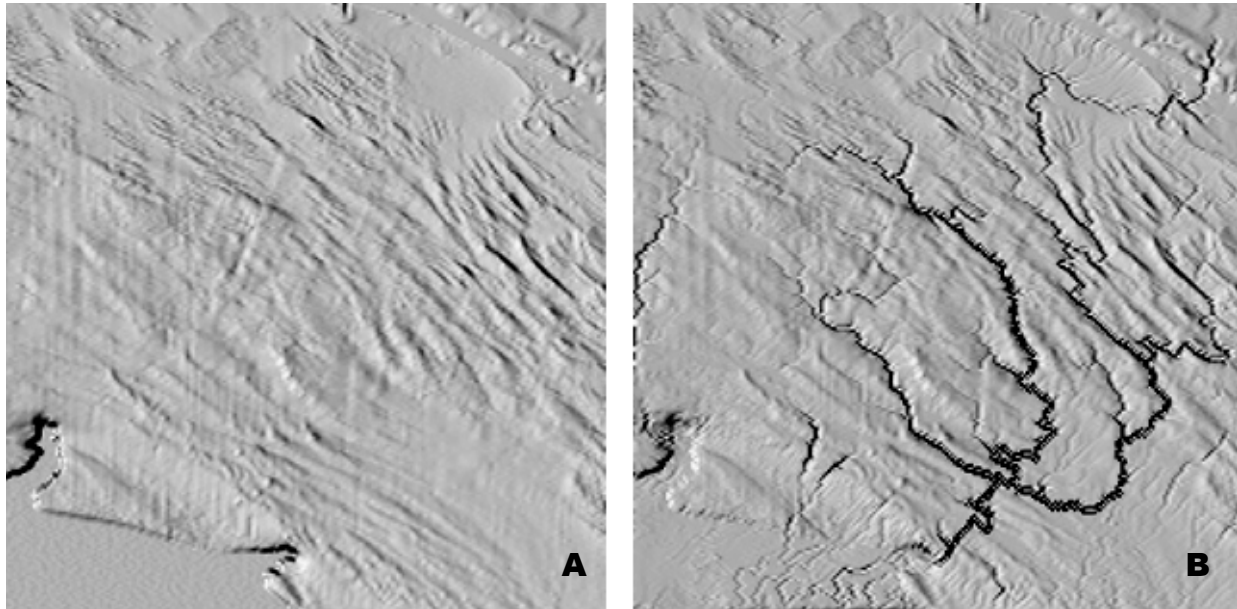
Figure 1. Simulations of channel development on an exposed continental shelf. The initial topography (A) is from the Virginia continental shelf. The channels shown in black in (B) are the result of 500 years of transport and incision.

- Initial topography strongly influences drainage patterns, in particular the reticulate drainage pattern, closed depressions, and channels eroding headwards from extant canyon heads. As sea level falls, waves and currents would probably modify the offshore topography prior to incision. It is likely that some simulated channels reoccupy courses of buried channels from earlier lowstands.

- Major dissection is limited to a few main channels, including up to 40 m of downcutting by gullies working headward from the shelf edge.

- The main drainage pattern is established early in the simulation.

- Depressions are infilled and eventually integrated into the drainage system.

- Dissection in the headwaters is initially largely independent from downstream erosion and deposition

An Implicit Finite-Difference Model for Drainage-Basin Evolution

The implementation of landscape evolution models is constrained by numerical instabilities. In the simplest models of basin evolution only two processes are present: a diffusive soil creep plus advective sediment transport in channels. Alluvial sediment transport is formulated as a function of drainage area, a surrogate for discharge and slope. When calculating sediment budgets at each node, the high variability of drainage area amplifies small variations in bottom slope leading to a solution that

requires very small time steps for numerical stability, thus limiting the model applicability for large spatial and temporal domains. In order to overcome these difficulties, an implicit finite-difference method was developed. The method solves the original equations for the alluvial transport adjusting simultaneously the bottom elevation in each node of the domain. The method is unconditionally stable, conserving sediment mass for any time step adopted. Computationally the implicit scheme is very efficient, reducing the CPU time by up to a factor 100 with respect to an explicit formulation. The method and results are described in Fagherazzi et al (in press).

In Figure 2 we show a test example. The starting topography is a tilted plane of constant gradient to which is added small random elevations. The upper, left, and right boundaries are impermeable to sediment and water whereas the lower boundary is kept at a constant elevation (Fig. 2A). Alluvial erosion forms a network of channels that drains the (Fig. 2B). Results obtained by the implicit and explicit method are similar, with the advantage that the implicit method requires only 10 iterations, against the 10000 iterations of the explicit scheme (Fig. 3B and 3C). Small differences arise because the scheme does not update the drainage area during a time step. Particular attention has to be paid in situations where the distribution of drainage area changes fast. In these cases, such as the first stages of channelization of flat surfaces or channel avulsion in alluvial depositional environments, a smaller time step in the implicit scheme is necessary to follow the transient dynamics.
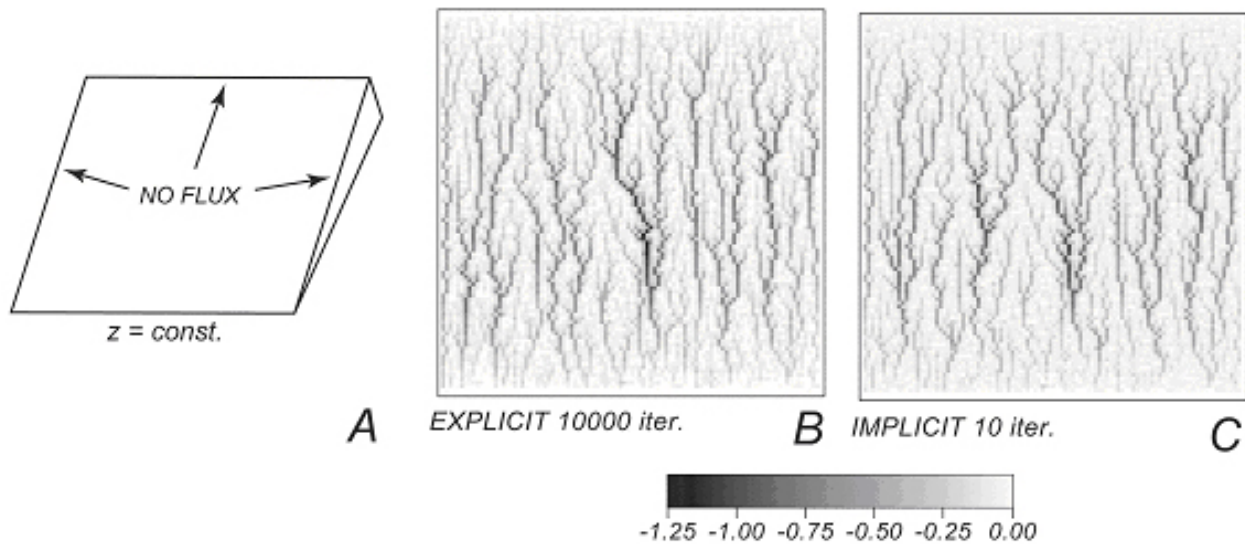
Figure 2. Drainage basin simulations on a(A) sloping plane using an (B) explicit and (C) implicit solution scheme. The implicit scheme is much more efficient (10 vs. 10000 iterations).

Modeling Virginia Coastal Plains – A Model Test

To understand the submarine morphology of the continental shelf, with particular emphasis on the buried network of riverine channels, it is necessary to study and model the corresponding subaerial coastal plains. Sea-level oscillations in the geological past have submerged and exposed the coastal plains. From this perspective, the actual continental shelf was once a coastal plain where precipitation and runoff created a network of rivers that has been subsequently filled with sediment during

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transgression. Thus coastal plain rivers, such as the Rappahannock River, Virginia, offer good analogues to rivers that we would expect to form on exposed shelves during sea-level low stands and comparison of characteristics of simulated river channels with geological and hydrological data from coastal plain rivers provides a test of the model. A number of data sets may be utilized to tune and validate the model, including: river discharge data, suspended sediment data, stratigraphy, and dating of alluvial terraces. We are currently assembling these types of data for the Rappahannock River to use as a test of the characteristics and evolution of channels produced in the model simulations.

Representing shelf sediment transport processes in a landscape evolution model

Forms of the diffusion equation are commonly used to represent geomorphic processes in terrestrial landscape evolution models. There are several ways to develop a diffusion-type formulation for shelf sediment transport. The approach adopted here, is to use available wave and current time series to calculate shelf diffusivities based on a distribution of random walks.   There are a number of sites on the California shelf (e.g., Eel R., Russian R., and Palos Verdes shelves) for which suitable data exist to test this approach. For example, on the Eel shelf, data from the long-term tripod at S-60 provide current data over 5 years, while the nearby NDBC Buoy 46022 has recorded 20 years of surface wave and weather conditions. To perform the calculations, a 14-day section of hourly currents is randomly selected from a time series of shelf currents. A hypothetical sediment particle is released from the site of interest at the beginning of the 14-day time series. For each hourly value of the current, determination is made as to whether the probability of wave resuspension is exceeded for the particle. If it is, the particle moves a distance equal to the hourly current times 3600 (s per hr). The probability of resuspension is determined for the particle's new location and the process is repeated for the next hour of currents.   This calculation is carried out for 500 particles released at random times in the current time series.

An example of the resulting distribution of travel distances in the across-shelf direction, are shown in Figure 3a. For a normally distributed variable, the diffusivity can be found from the standard deviation of the resulting distribution. Figure 3b shows calculated along- and across-shelf diffusivities calculated for site S-60 on the Eel shelf. Comparable calculations at other shelf sites suggests that the diffusivities obtain through this procedure provide a good measure of shelf sediment transport potential. Work has just begun on incorporating this representation of shelf processes into the landscale evolution model.
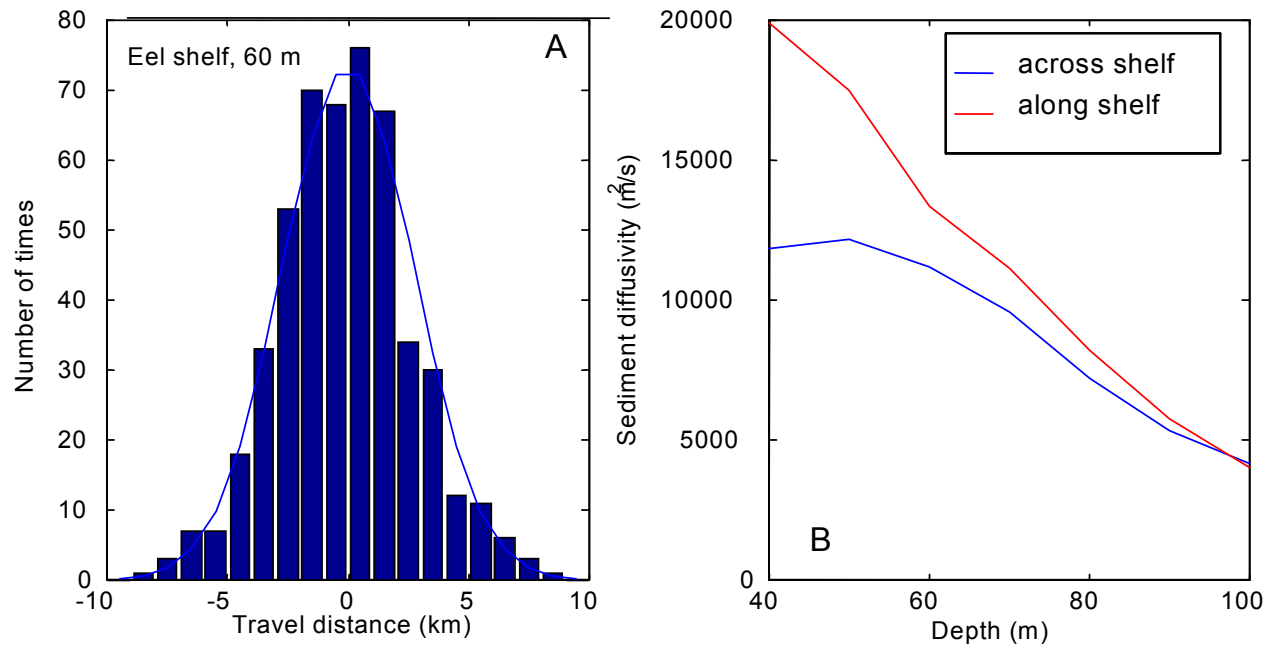
Figure 4. (A) Distribution of across-shelf travel distances of particles moving in response to wave and current conditions on the Eel shelf. (B) Along and across-shelf sediment diffusivities calculated from the travel-distance distributions; diffusivities decrease with increasing water depth.

IMPACT/APPLICATIONS

Model simulations provide information about channel incision rate, channel density, and channel burial for acoustic analyses of buried channel features on the continental shelf that contribute to geoclutter.

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PUBLICATIONS

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